The Blue Diamond Landslide: Evidence of a Multi-Phase Emplacement for a Large-Scale Landslide

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Abstract

Remnants of the Blue Diamond landslide breccia are exposed throughout the foothills of the eastern Spring Mountains near Blue Diamond, Nevada. Uncertainties surrounding the origin and emplacement of the of the ancestral landslide have emerged based on the disparate distribution of landslide outcrops. This study uses detailed sedimentological data and observations to interpret a two-phase emplacement history for the Blue Diamond landslide.

Sedimentological observations of a discontinuous basal facies, shear features, high matrix contents, and crackle and jigsaw breccia textures indicate that the Blue Diamond landslide breccia was emplaced as a rock avalanche. The presence of clastic dikes and flame structures suggest runout occurred over a saturated substrate. Flow transformation into a debris avalanche is ruled out because clast count data show that debris entrainment (< 2%) was not sufficient enough to act as the sole mechanism behind the excessive mobility experienced by the Blue Diamond landslide. Instead, we propose that the excessive mobility was driven by flow entrainment of large Aztec Sandstone boulders and interaction with a saturated runout path substrate that caused a reduced basal frictional resistance, enabling emplacement onto Blue Diamond Hill. We therefore suggest that the landslide breccia was derived from a source area 8.5 km northwest of the Blue Diamond townsite and flowed into the Blue Diamond Hill site where it was deposited onto Moenkopi Formation atop the hill during the Miocene. Due to the new overburden, incompetent gypsum horizons failed within the upper Kaibab Formation stratigraphically below the Moenkopi Formation. These failed gypsum horizons then served as a rupture surface suitable enough to initiate a compound landslide consisting of the overlying Moenkopi Formation and landslide breccia. Emplacement was driven by the head of the Blue Diamond slide block as it slid into its current position in the Blue Diamond area. This secondary emplacement likely ceased by late Miocene to Pliocene time.

Background

Many long-runout landslide and slide-block deposits have been identified in the Basin and Range province as landslide breccia deposits (Fig. 1A; e.g., Burchfiel et al., 1974). These distinctive breccias comprise a volumetrically significant amount of Cenozoic deposits in the Miocene extensional basins; however, slide blocks are often obscure in the geologic record (Wills and Anders, 1999). Some of the slide blocks are so large that they can be mistaken for tectonic structures (Biek et al., 2019). Therefore, their identification and understanding their depositional significance is important to our understanding of the evolution of the Basin and Range province and will help us better identify older deposits.

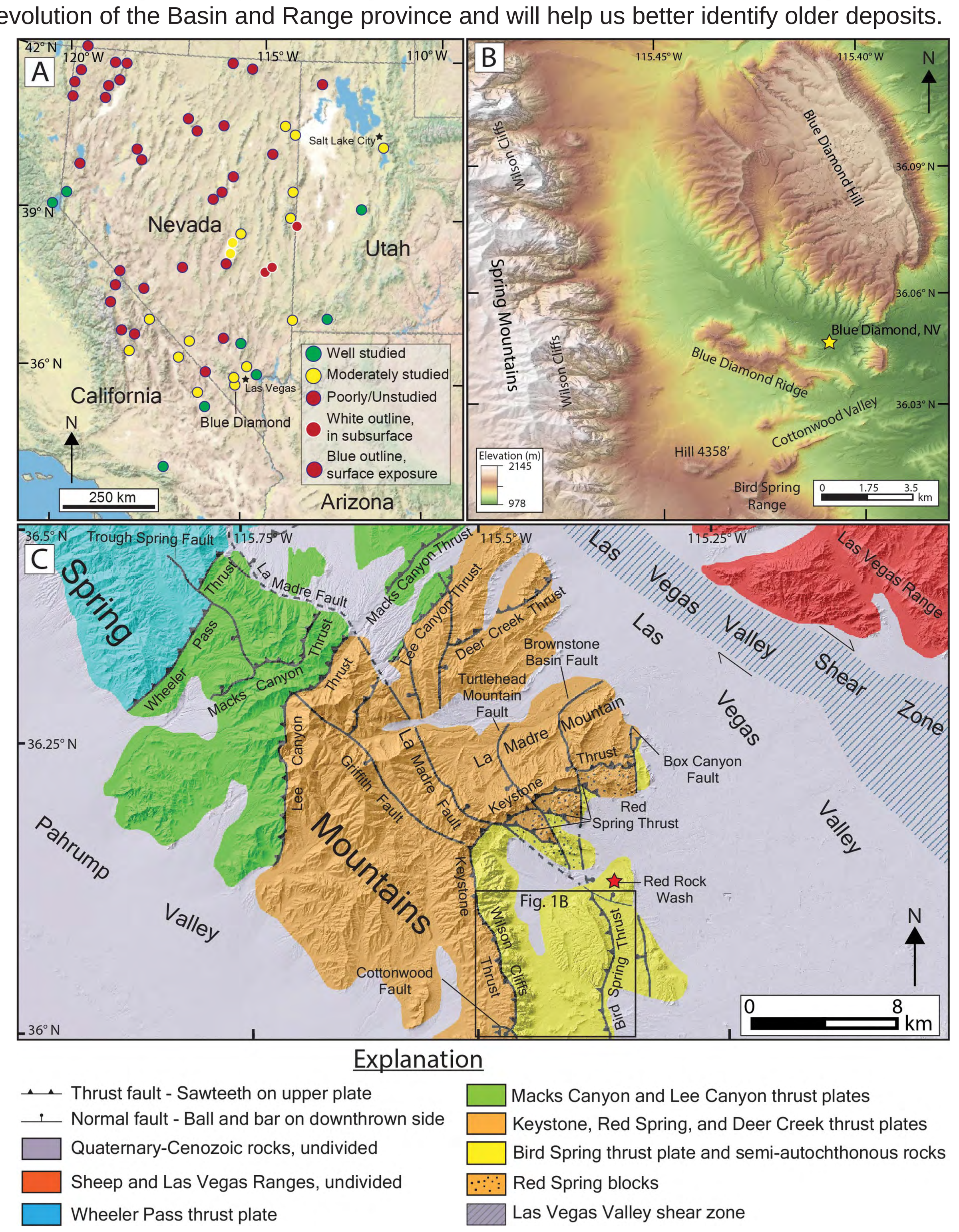

Figure 1. A) Some of the known large landslide deposits in the Basin and Range and the degree of their study. B) Surficial digital elevation map showing the location of the study area and local topography. C) Map of Sevier thrusts in the Spring Mountains and other major structures in the Las Vegas Valley area showing location of Part B (from Ferry et al., 2022).

Definitions

Several terms (i.e., megabreccia, sturzstrom, slide block) have been applied to large-scale landslide deposits. In this we use landslide terminology *sensu* Hungr et al. (2014), as summarized here.

Rock Avalanches:
- Velocity: > 5 m/s (extremely rapid)
- Volume: > 10^6 m^3 of fragmented rock
- Type of Movement: flow
- Key Characteristic: excessive mobility

Rock Compound Slides:
- Velocity: 1.6 m/year to 1.6x10^4 m/year (slow)
- Volume: 10^6 m^3 to 10^9 m^3 of coherent blocks
- Type of Movement: slide
- Key Characteristics: horst-and-graben features at head, rupture surface at toe, maintain a coherent internal stratigraphy

Blue Diamond Landslide

The Blue Diamond landslide breccia is exposed in the foothills of the eastern Spring Mountains (Fig. 1). Landslide breccia caps several low hills and ridges, in addition to having two small exposures atop Blue Diamond Hill (Figs. 2a, 3). Encompassing all breccia outcrops, the ancestral landslide deposit is projected to have covered an area of 25 km^2 in the Blue Diamond area. The distribution of landslide breccia remnants raises many questions over the source area, age, and emplacement of the Blue Diamond landslide.

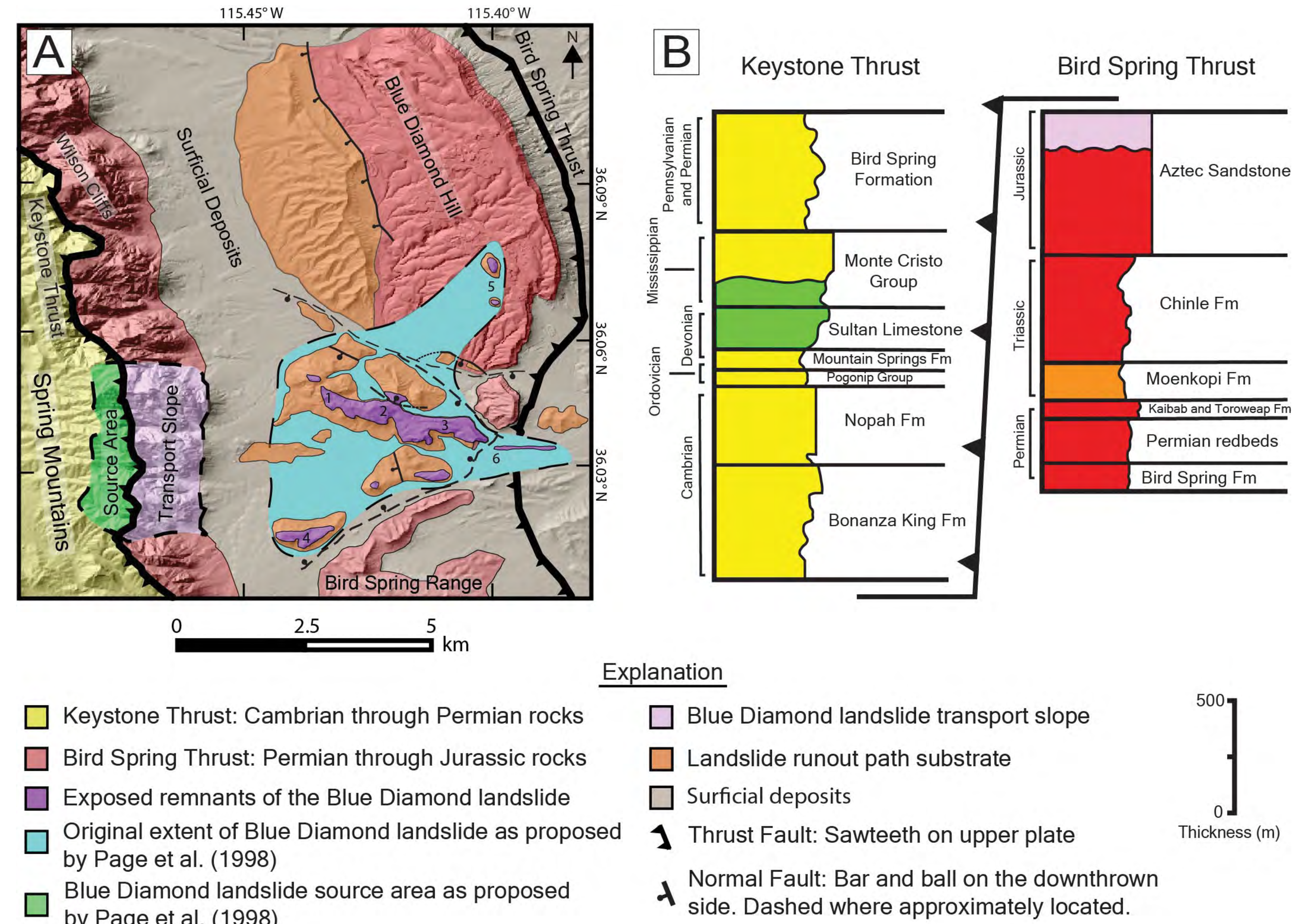

Figure 2. A) Digital elevation map showing the current exposed remnants of the Blue Diamond landslide and the original distribution and source area of the landslide as proposed by Page et al. (1998). Dashed lines are projected areas as proposed by Page et al. (1998). Same location as Fig. 1B. Numbers represent the general vicinity in which clast counts and facies observations were grouped (1, proximal Blue Diamond Ridge; 2, medial Blue Diamond Ridge; 3, distal Blue Diamond Ridge; 4, Hill 4358'; 5, Blue Diamond Hill; 6, eastern Cottonwood Valley). B) Generalized stratigraphic columns for the Keystone and Bird Spring thrust sheets in the study area (from Ferry et al., 2022).

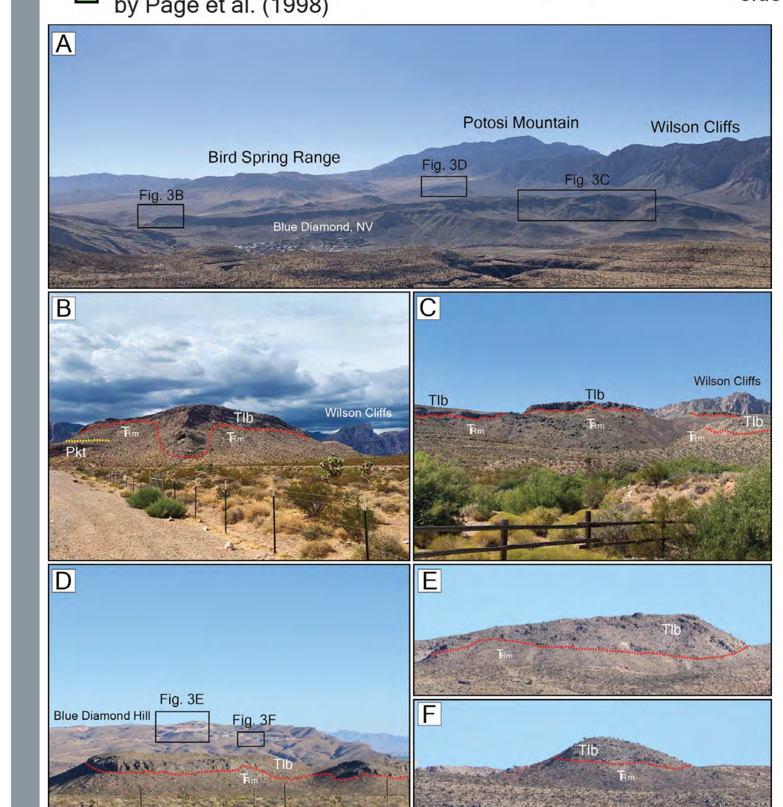

Figure 3. Deposit outcrops throughout the Blue Diamond area: A) view of the 4-km-long Blue Diamond Ridge and Hill 4358', B) distal at Blue Diamond Ridge (Tlb, Blue Diamond landslide breccia; TRm, Moenkopi Formation; Pkt, Kaibab-Toroweap Formation), C) proximal at Blue Diamond Ridge, D) proximal at Hill 4358' location, E) northernmost outcrop atop Blue Diamond Hill, F) southernmost outcrop atop Blue Diamond Hill (from Ferry et al., 2022).

Methods

In this study, we use clast counting, facies analysis, and field observations to interpret the provenance and emplacement mechanism(s) of the Blue Diamond landslide breccia.

Facies Model

Yarnold and Lombard (1989) developed a set of descriptive facies for landslide deposits that formed in arid environments (Fig. 6). Their work suggests a lateral zonation of sedimentological features that they interpret to result from the emplacement mechanisms of large rock avalanches and the rheological properties of the runout path substrate.

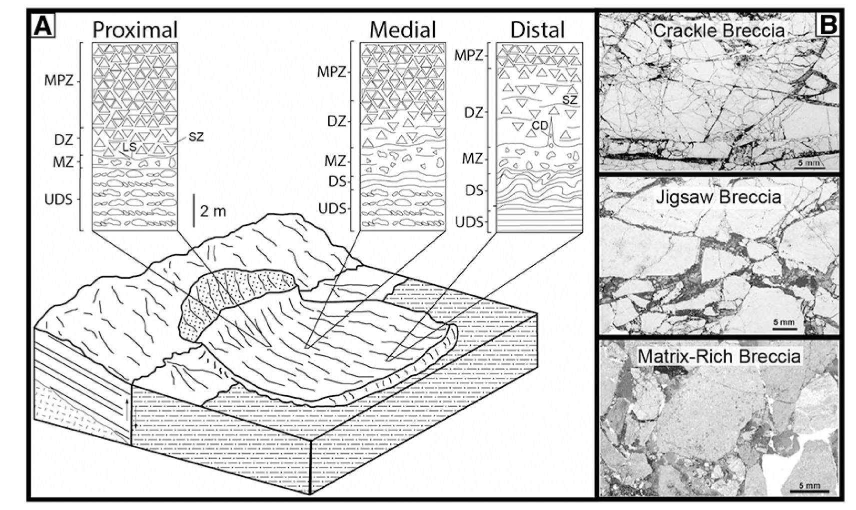

Figure 4. A) Idealized morphology of rock avalanche deposits formed in arid climates showing characteristic features at each lateral zone; undistrubed substrate (UDS); disturbed substrate (DS); mixed zone (MZ); disrupted zone (DZ); and a matrix-poor zone (MPZ) that features shear zones (SZ); clastic dikes (CD); and load structures (LS). B) Large rock avalanche breccia sheet lithofacies in proper stacking order (from Ferry and Sturmer, 2022).

Results

Clast Counts

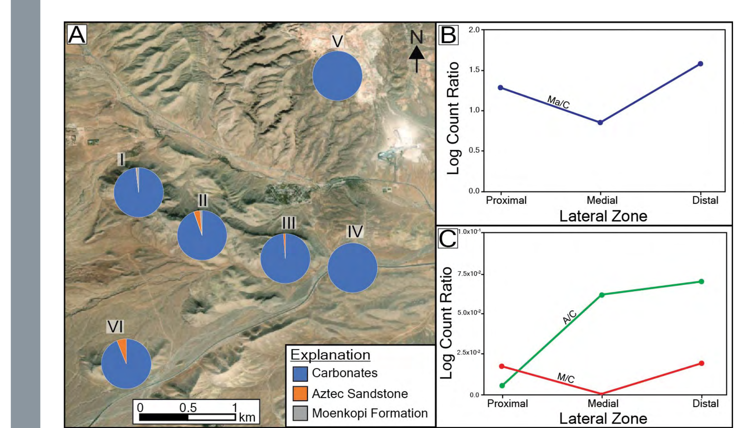

Table 1. Total clast-count data for Blue Diamond landslide breccia with separate count data for each outcrop counting region from Figure 5a.

	Total			Hill 4358′			Blue Diamond Hill			Cottonwood Valley		
Clast Type	*n*	%	*CI*	*n*	%	*CI*	*n*	%	*CI*	*n*	%	*CI*
Carbonates	6510	54.8	3.1	445	49.4	10.6	476	66.1	14.3	267	74.2	19.9
Matrix	5173	43.5	2.9	426	47.3	7.2	244	33.9	14.3	93	25.8	19.9
Aztec	149	1.3	0.6	29	3.2	4.1	0	0.0	0.0	0	0.0	0.0
Moenkopi	48	0.4	0.2	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
N	11880	–	–	900	–	–	720	–	–	360	–	–
K	132	–	–	10	–	–	8	–	–	4	–	–
	Blue Diamond Ridge			Proximal			Medial			Distal		
Clast Type	*n*	%	*CI*	*n*	%	*CI*	*n*	%	*CI*	*n*	%	*CI*
Carbonates	5322	53.8	3.3	1254	49.8	6.5	2136	56.5	4.3	1932	53.7	6.6
Matrix	4410	44.5	3.2	1243	49.3	6.1	1522	40.3	3.8	1645	45.7	6.4
Aztec	120	1.2	0.6	5	0.2	1.3	92	2.4	1.4	23	0.6	0.6
Moenkopi	48	0.5	0.3	18	0.7	0.6	30	0.8	0.6	0	0.0	0.0
N	9900	–	–	2520	–	–	3780	–	–	3600	–	–
K	110	–	–	28	–	–	42	–	–	40	–	–

Symbols: n, *total individual clast group counts;* %, *clast contribution percentage;* CI, *confidence interval (%);* N, *total individual counts;* K, *total counting stations.*

Figure 5. A) Map of general counting zones and the relative proportions of carbonate, Aztec SS, and Moenkopi Fm clasts. I) proximal Blue Diamond Ridge, II) medial Blue Diamond Ridge, III) distal Blue Diamond Ridge, IV) eastern Cottonwood Valley, V) Blue Diamond Hill, and IV) Hill 4358' (from Ferry and Sturmer, 2022). B, C) Ratio analysis of clast counts in landslide breccia along a W-E transect in Blue Diamond Ridge. Clast populations: carbonate (C), matrix (Ma), Aztec SS (A), Moenkopi Fm (M).

Facies Analysis

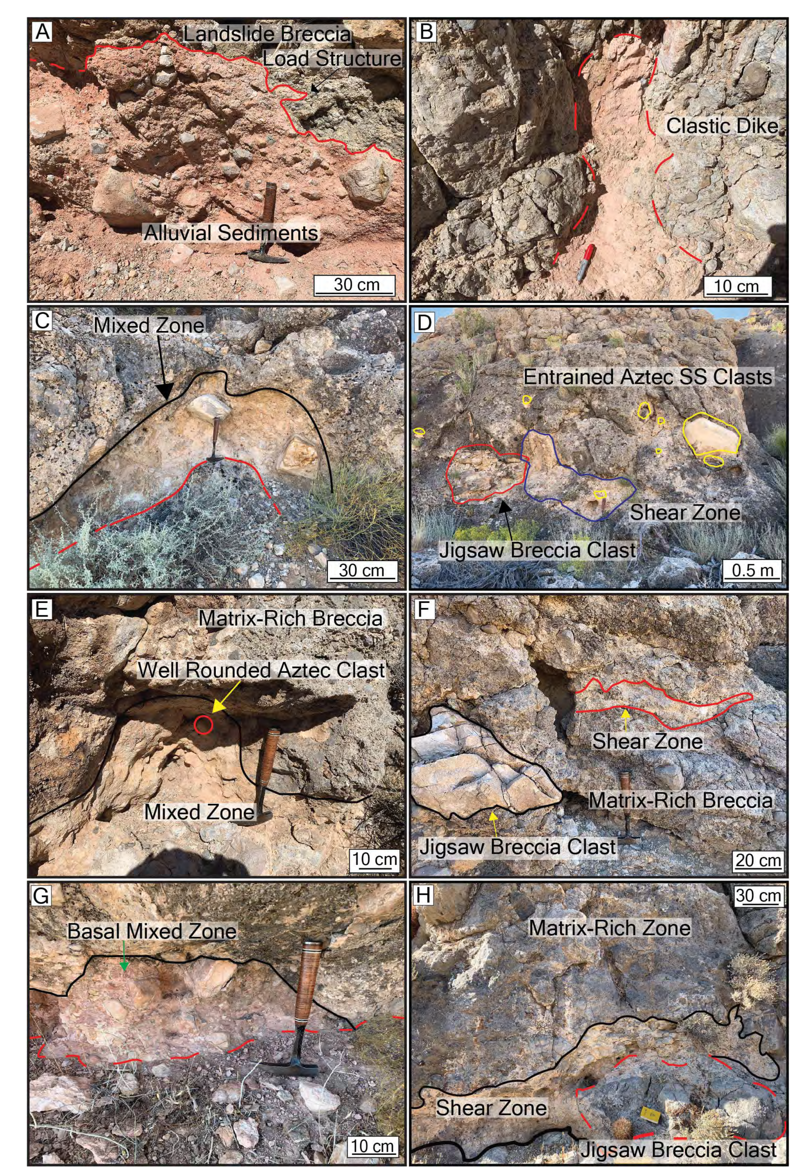

Figure 6. Textural features of the Blue Diamond landslide. Proximal Blue Diamond Ridge: A) disturbed alluvial substrate and B) clastick dike derived from mixed zone penetrating disrupted zone. Medial Blue Diamond Ridge: C) undulatory mixed zone, D) 7-m-thick disrupted zone with significantly more entrained Aztec SS clasts than in proximal or distal zones. Distal Blue Diamond Ridge: E) undulatory mixed zone with entrained clasts and F) disrupted zone with entrained jigsaw breccia clasts and shear zone. Hill 4358': G) basal mixed zone with entrained Aztec SS clasts and H) shear zone in the matrix-poor zone.

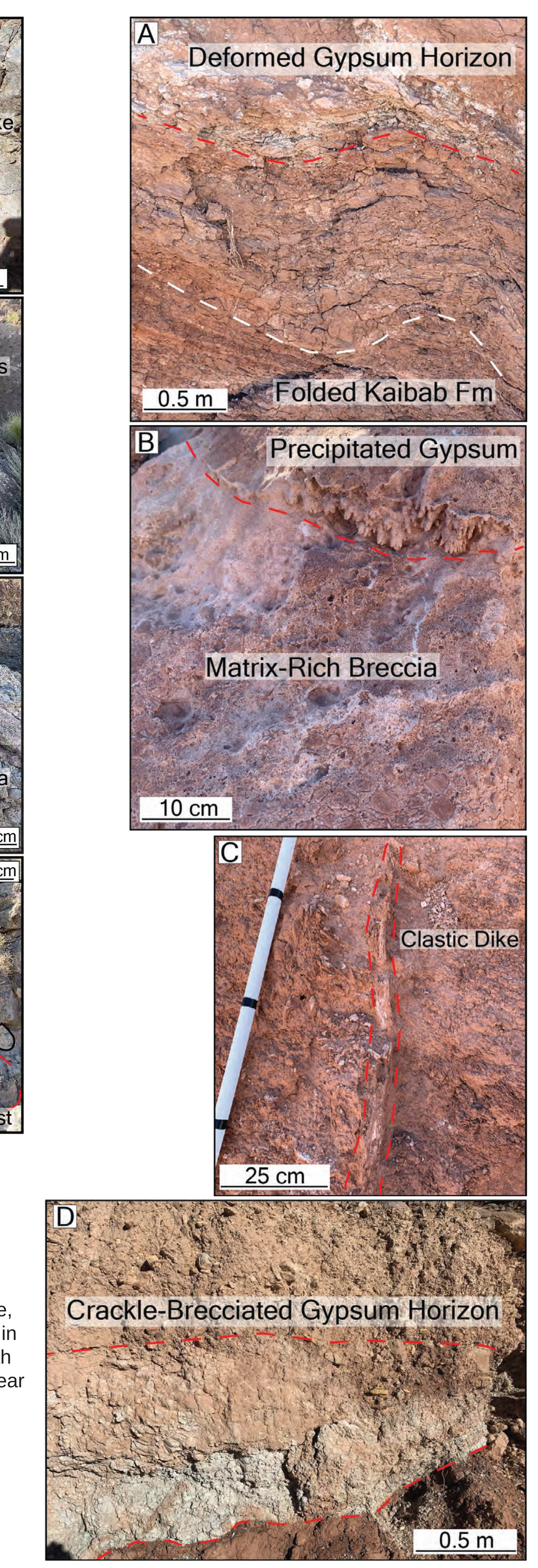

Figure 7. Textural features of Kaibab Formation underlying landslide breccia and Moenkopi Formation on Blue Diamond Hill: A) deformed carbonate strata and gypsum horizon. B) Matrix-rich breccia draped with gypsum, C) clastic-dike penetrating matrix-poor breccia, D) gypsum horizaon displaying crackle-breccia facies.

Discussion

A Model for Emplacement

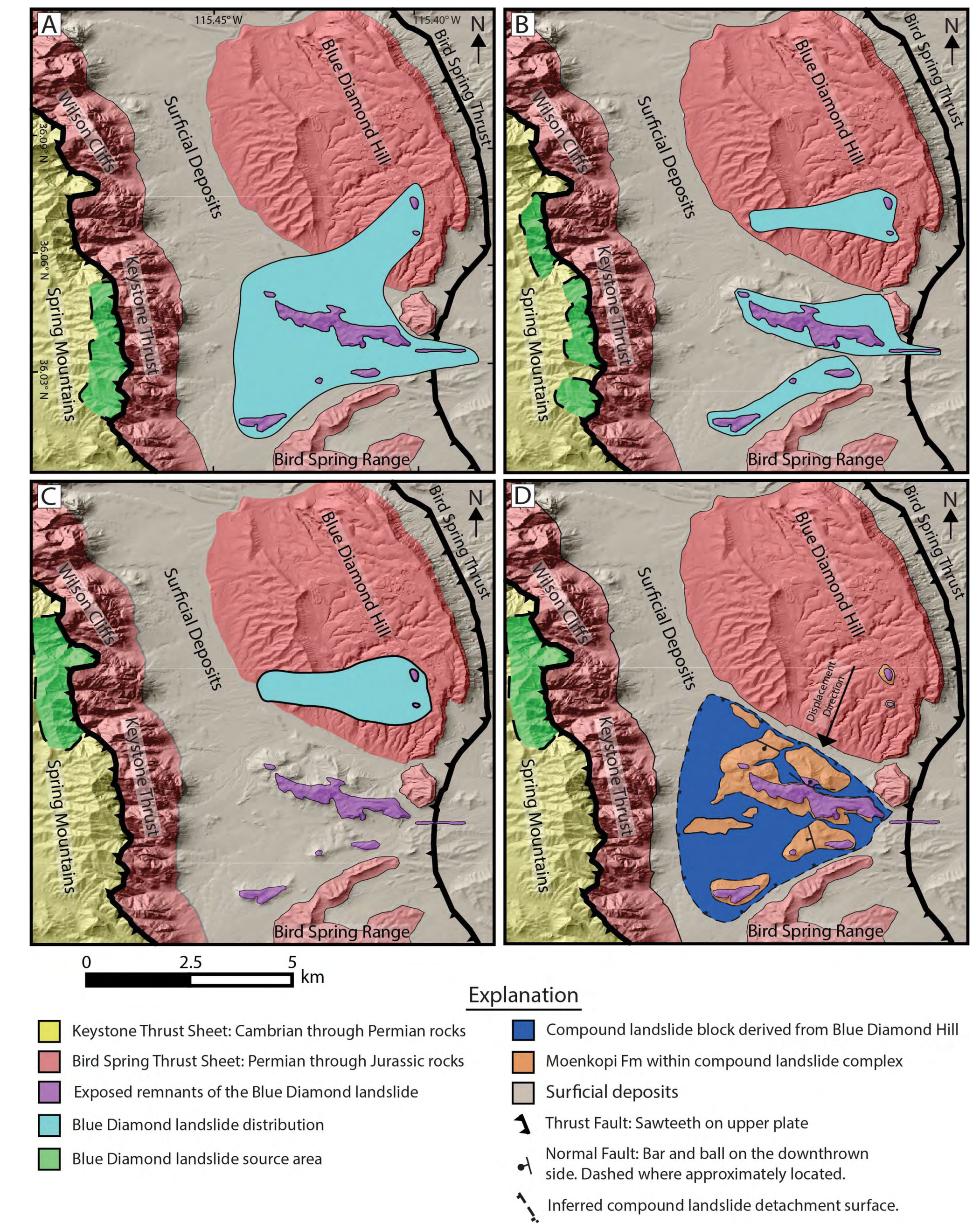

Figure 8. Map view of A) Page et al. (1998) interpretation of source area and original deposit extent. B) Multiple-landslide model. C) Model of northern source area and rock-avalanche emplacement onto Blue Diamond Hill. D) Detachment on gypsum-bearing substrate and subsequent compound landslide emplacement to present configuration. Same location as Figure 1b.

Parameter	Page et al. (1998)	Our Hypothesis	[1]Hill 4358′	[1]Blue Diamond Ridge	[1]Blue Diamond Hill
Deposit Volume, *V* (m^3)	5.0×10^8	1.5×10^8	1.3×10^8	4.4×10^8	?
Source Area Volume (m^3)	2.1×10^8	1.5×10^8	2.9×10^7	2.2×10^7	6.7×10^7
Deposit Length (m)	6070	4103	3950	5810	?
Fall Height, *H* (m)	925	563	859	802	575
Runout Length, *L* (m)	9624	9750	7370	1110	7370
H/L Ratio	0.10	0.06	0.12	0.07	0.06
Fahrböschung ($\tan^{-1}$ H/L)	5.7°	3.4°	6.6°	4.1°	3.4°

[1] Part of multiple-landslide model.

Table 2. Estimates of emplacement parameters of the Blue Diamond landslide.

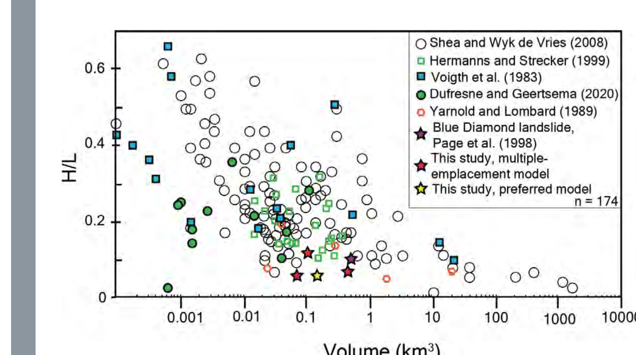

Figure 9. H/L versus slide volume compiled from published data and compared with the three models presented in this paper for the Blue Diamond landslide. Data are compiled from Voight et al. (1983), Yarnold and Lombard (1989), Hermanns and Strecker (1999), Shea and van Wyk de Vries (2008), and Dufresne and Geertsema (2020).

Conclusions

We present a multi-stage model for emplacement history of the Blue Diamond landslide deposit in southern Nevada, in the Basin and Range province:

1). Observations of a discontinuous basal facies, shear zones, and crackle, jigsaw, and matrix-rich breccia textures indicate that the landslide was emplaced as a rock avalanche.

2). The Blue diamond landslide was derived from a source area about 8.5 km northwest of the Blue Diamond townsite.

3). The Blue Diamond landslide experienced excessive mobility which allowed it to travel a total of 9.5 km and clim up Blue Diamond Hill for nearly 4 km before it was deposited on Moenkopi Fm atop the hill. This excessive mobility was achieved by an increase in runout potential through entrainment of Aztec SS clasts from the Wilson Cliffs and a low resistance to motion due to emplacement over a saturated substrate.

4). Overburden from the newly deposited landslide breccia resulted in the failure of gypsum horizons in the Upper Kaibab Fm that underlie the Moenkopie Fm. With the rupture gypsum horizons serving as a slide surface, the shallow dip of Blue Diamond Hill was adequate to initiate compound-landslide emplacement of a slide block consisting of Moenkopi Fm and the overlying landslide breccia. The Blue Diamond slide block was then transported from Blue Diamond Hill into its current position in the Blue Diamond area.